Expansion of FRT Operation Range for Grid-Tied Matrix Converter System

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***Abstract*— This paper proposes a control method to expand a fault-ride-through (FRT) operation range for a grid-tied matrix converter. In the conventional method, the generator current is limited because the q-axis current is only controlled whereas the d-axis current is kept to zero. Consequently, the matrix converter cannot satisfy the FRT requirements for the grid reactive current due to the limitation of the generator current. Therefore, in the proposed method, the d-axis current is injected in order to be able to increase the generator current as well as the grid reactive current. This results increase the maximum grid reactive current by 15% as compared to that of the conventional method. From the simulation and experimental results, the proposed method expands the FRT operation range from 43 % to 100%, the FRT operation range is expanded by 57pt.**

Keywords—matrix converter; fault ride through; generator; reactive current; three-phase voltage sag

I. INTRODUCTION

Nowadays, a wind turbine system and a distributed power generation system, a low-head hydro power unit have attracted many attentions as a sustainable energy system [1]. In these systems, the fault-ride-through (FRT) requirements for the grid-tied converters are applied in many countries in order to avoid a power interruption in a large scale when only a local grid fault occurs [2]. A power converter of the grid-tied system employed must satisfy the FRT requirements as following: 1) the grid-tied converter needs to continue to operate during the grid voltage sag when the remaining voltage and its duration are within a limitation defined by the grid requirements; 2) a reactive current is delivered to the grid dependently on the remaining voltage. Moreover, in the wind turbine system, the generator torque needs to be maintained regardless of the grid state in order to avoid unexpected acceleration and vibration of the wind turbine [3]. In addition, in the distributed power generation system and the low-head hydro power unit, the generator cannot react to a quick torque disturbance caused by the grid voltage sag [4]. Thus, the grid-tied converter is also required the following capability aside from the FRT requirements: 3) the grid-tied converter has to maintain the generator torque during the grid voltage sag as same as that in the normal operation.

Meanwhile, a matrix converter has also attracted many attentions as a high-performance AC-AC converter [5-8]. The matrix converter is expected to achieve higher efficiency, smaller size and longer life-time compared to a conventional back-to-back (BTB) system. In previous works, grid-tied systems using the matrix converter for the wind turbine or the distributed power generation system have been reported [9-11]. However, generator terminal voltage of the grid connected matrix converter is forced to be lower during the grid voltage sag because the matrix converter is a step-down converter. Thus, it is difficult for the matrix converter to realize the FRT operation.

Some literatures about the FRT method of the matrix converter have been published [12-19]. A conventional FRT control method for the matrix converter has been proposed to achieve 1) the stable FRT operation, 2) the grid reactive current control and 3) the generator torque control in the same time during the voltage sag [19]. However, in this control method, the generator current amplitude is limited because the active (q-axis) current is only controlled whereas the reactive (d-axis) current is kept to zero. Consequently, the matrix converter cannot satisfy the FRT conditions of more than the voltage sag of 43% for the grid current due to the limitation of the generator current.

This paper proposes a control method to expand a FRT operation range for the grid-tied matrix converter. The q-axis current is flown into the snubber circuit and the d-axis current is flown into a voltage source inverter (VSI) of an indirect matrix converter (IMC). The proposed method maintains the q-axis current and increases the d-axis current of the generator in order to increase the generator current. In consequence, the grid reactive current can be increased in order to expand the FRT operation range. This paper is organized as following; first the control strategy of the grid-tied matrix converter during the FRT operation is explained. Second, the control of the d-axis current in the generator to increase the grid reactive current is explained. Finally, the effectiveness of the proposed control method is confirmed by the simulation and experiments.

II. Circuit Configuration

Fig. 1 shows the matrix converter which is used for an interface converter between the power grid and the generator. During the voltage sag, the active power supplied from the generator to the grid becomes zero because only the reactive current is flown to the grid. However, the same torque of the generator should be maintained as same as that before the voltage sag. Therefore, a brake system consisting of an IGBT and a braking resistor is employed in order to absorb the active power provided from the generator. In particular, the IGBT in the brake circuit is turned on during the voltage sag and the active power provided from the generator is consumed by the braking resistor R_{brk}. It is note that this braking circuit is required not only in the system employing the matrix converter but also in the conventional BTB system. Hence, the advantages of the matrix converter compared to the conventional BTB system does not degrade.

III. Fault-Ride-Through Control Method for Grid-Tied Matrix Converter

Fig. 2 shows a circuit diagram of the indirect matrix converter (IMC) which is used to employ the proposed FRT method. The modulation method for the matrix converter during the voltage sag uses a virtual indirect control method [5]. The virtual indirect control treats the matrix converter illustrated in Fig. 1 as the IMC which consists of a current source rectifier (CSR) and the voltage source inverter (VSI). This replacement simplifies a consideration about the modulation method during the voltage sag. Note that the LC filters is eliminated and the snubber circuit is composed of a diode bridge and a DC voltage source in Fig. 2. Then, in order to yield the same waveforms between the matrix converter and the IMC at the input and output terminals excluding an effect of the LC filter in Fig. 1, (1) should be satisfied.

$$\begin{bmatrix} S_{ru} & S_{su} & S_{tu} \\ S_{rv} & S_{sv} & S_{tv} \\ S_{rw} & S_{sw} & S_{tw} \end{bmatrix} = \begin{bmatrix} S_{up} & S_{un} \\ S_{vp} & S_{vn} \\ S_{wp} & S_{wn} \end{bmatrix} \begin{bmatrix} S_{rp} & S_{sp} & S_{tp} \\ S_{rn} & S_{sn} & S_{tn} \end{bmatrix} \quad \text{...............(1)}$$

Fig. 3 shows a modulation block diagram of the matrix converter for the FRT operation. A single-phase modulation is employed to the CSR in order to modify the grid power factor reference during the voltage sag [5]. This results in the same modulation scheme of the CSR in both the grid normal operation and the voltage sag. On the other hand, the VSI has to change the modulation strategy in response to the grid state.

Fig. 4 shows the operation of the VSI in the voltage sag. In the conventional method, the generator current is limited because the q-axis current is only controlled whereas the d-axis current is kept to zero. Consequently, the matrix converter cannot satisfy the FRT requirements for the grid reactive current due to the limitation of the generator current. Therefore, in the proposed method, the generator current as well as the grid reactive current is increased due to inject the d-axis current. In order to adjust the d-axis current, the control of the matrix converter is separated into three modes; a) the generator power factor control mode (only one line is short-circuit), b) the DC-link conduction mode, and c) the freewheeling mode. In a) the

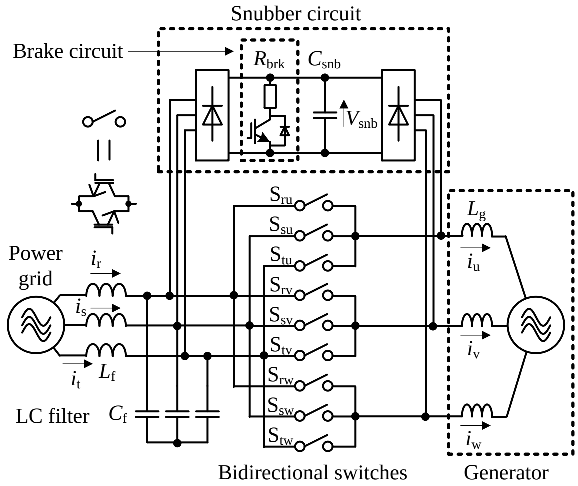

Fig.1. Circuit configuration of a matrix converter.

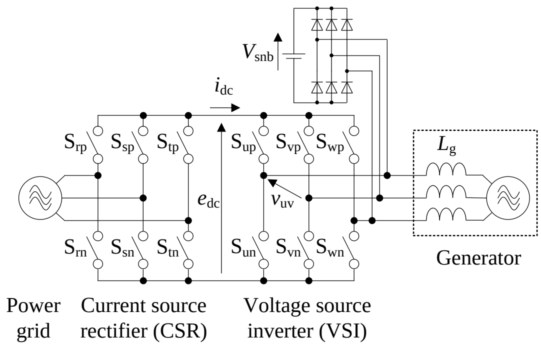

Fig.2. Circuit diagram of indirect matrix converter.

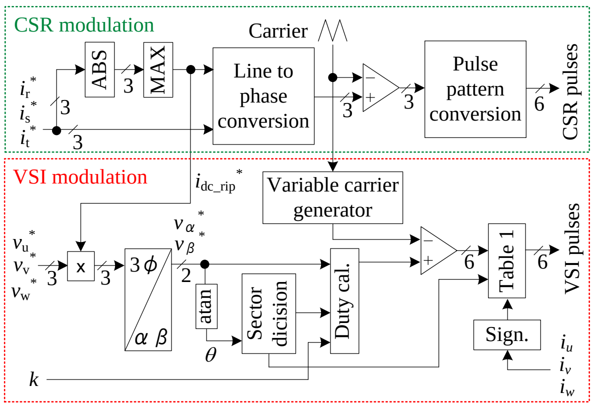

Fig.3. Modulation block diagram in FRT mode.

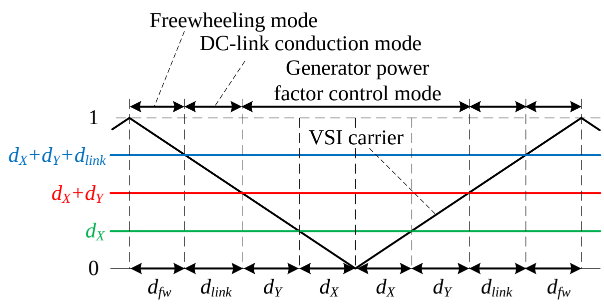

Fig.4. VSI operation in short voltage sag.

generator power factor control mode, the dq-axis currents of the generator are controlled. In b) the DC-link conduction mode, the VSI and the CSR are connected in order to let the grid reactive current circulate in the matrix converter. On the other hand, c) the freewheeling mode let the reactive current circulate only in the VSI, which helps adjust the amplitude of the grid reactive current.

a) Mode 1: Generator power factor control mode

Fig. 5 shows an equivalent circuit of VSI and the snubber circuit in the generator power factor control mode. In this mode, the virtual DC-link voltage becomes zero because the active power on the power grid is zero during the voltage sag. Therefore, the CSR is not considered in Fig. 5. The q-axis current is flown into the snubber circuit and the reactive d-axis current is flown into the VSI. In the conventional FRT method, the VSI switches are controlled in only two states; all turned on or all turned off. On the other words, the d-axis current in the conventional method is always zero, i.e. the unity power factor of the generator. Therefore, the VSI is modulated in order to adjust the d-axis current in the proposed method. This enables the control of the generator power factor, and then increases the generator current.

Table I shows the VSI pulse generation based on the conduction states of the diode rectifier during the generator power factor control mode. By selecting the short-circuit pathway of the generator, the current direction flow into the diode rectifier and the generator voltages are controlled, i.e. the control of the d-axis current. In particular, the conduction states of the diode rectifier define six space vectors from V1 to V6. The VSI controls the generator power factor by a current regulator (ACR) as following; two vectors from V1 to V6 which are adjacent to the voltage references v_α^*, v_β^* are selected. Then the duties d_X , d_Y of the output voltage vector v_X , v_Y are expressed by (2) and (3) based on these two selected vectors, whereas the DC-link conduction duty d_{link} is expressed by (4), and the freewheeling duty d_{fw} is expressed by (5).

$$d_X = \left|v_\alpha v_{Y\beta} - v_{Y\alpha} v_\beta\right| / \left|v_{X\alpha} v_{Y\beta} - v_{Y\alpha} v_{X\beta}\right| \quad \text{(2)}$$

$$d_Y = \left|v_{X\alpha} v_\beta - v_\alpha v_{X\beta}\right| / \left|v_{X\alpha} v_{Y\beta} - v_{Y\alpha} v_{X\beta}\right| \quad \text{(3)}$$

$$d_{link} = k(1 - d_X - d_Y) \quad (0 \le k \le 1) \quad \text{(4)}$$

$$d_{fw} = (1-k)(1 - d_X - d_Y) \quad (0 \le k \le 1) \quad \text{(5)}$$

where k is a constant decided by the ratio between the DC-link conduction mode and the freewheeling mode. Therefore, k adjusts the amplitude of the grid reactive current. In summary, the proposed method maintains q-axis current to be constant and increases the d-axis current of the generator by controlling the generator power factor. Thus the generator current amplitude is increased, which leads to the increase in the maximum grid reactive current. However, the achievable range of the generator power factor is still limited to be less than cos $\pi/6$ due to the limitation of the current flowing into the diode rectifier.

b) Mode 2: DC-link conduction mode

Fig. 6 shows a current path in the dc-link conduction mode. This mode is controlled by the dc-link conduction duty d_{link}. In the case of Fig. 6, the dc-link current i_{dc} becomes the u-phase current i_{u}. Therefore, the constant i_{dc} is obtained by changing the VSI vector, and the average voltage of the dc-link is zero per 1/6 of the grid period. Consequently, by using this mode, the constant dc-link current is obtained and the generator terminal voltage equals to the dc-link voltage, because all phases of the generator side are connected to the dc-link.

c) Mode 3: Freewheeling mode

Fig. 7 shows a current path in the freewheeling mode. In this mode, a zero vector is chosen to obtain a circulating path

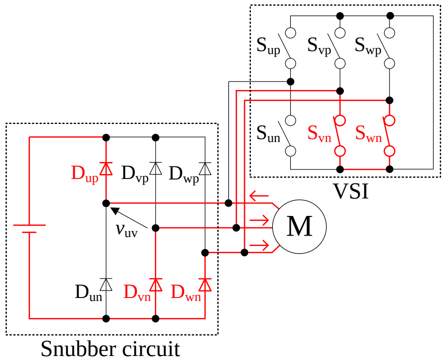

Fig.5. Equivalent circuit for VSI of IMC and snubber circuit.

Table I. VSI pulse table.

Conduction state of diode rectifier $[D_u, D_v, D_p]$	VSI pulse (S_u, S_v, S_w)	Conduction state of diode rectifier $[D_u, D_v, D_p]$	VSI pulse (S_u, S_v, S_w)
V1 [1 0 0]	(X 0 0)	V4 [0 1 1]	(X 1 1)
V2 [1 1 0]	(1 1 X)	V5 [0 0 1]	(0 0 X)
V3 [0 1 0]	(0 X 0)	V6 [1 0 1]	(1 X 1)

※ 1:Upper arm (D_{xp}, S_{xp}) ON 0:Lower arm (D_{xn}, S_{xn}) ON X:OPEN
x = u,v,w

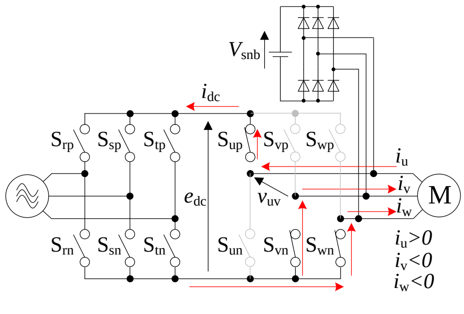

Fig.6. Current path in DC-link conduction mode.

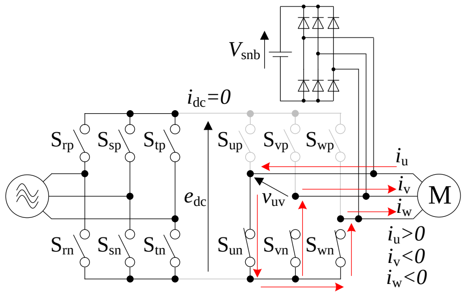

Fig.7. Current path in freewheeling mode.

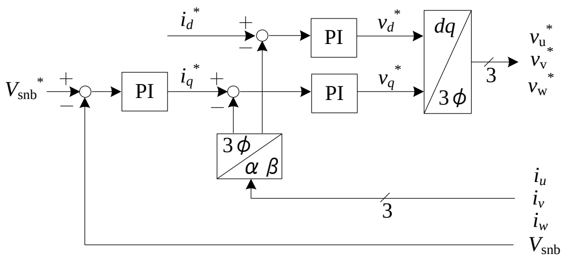

Fig.8. Control block diagram for snubber voltage control and generator current control.

Table II. Conditions of simulation and experiment.

Input line voltage	200 V	FRT duration	100 ms
Rated power	1500 W	Voltage sag	30%
Snubber voltage	400 V	Carrier frequency	10 kHz
Grid side filter L (L_f)	2.15 mH (2.53%)	Generator back e.m.f.	140 V
Grid side filter C (C_f)	7.92 μF (6.64%)	Generator inductance (L_g)	3.86 mH (9.28%)

Table III. Feedback control parameters.

Normal mode (Field oriented control)		d-axis current reference	0 p.u.
		q-axis current reference	-1.0 p.u.
		Proportional gain	1.2 p.u.
		Integral time	26.6 ms
FRT mode	Snubber voltage control	Voltage reference	400 V
		Proportional gain	2.0 p.u.
		Integral time	16.5 ms
	Generator current control	d-axis current reference	-0.577 p.u.
		Proportional gain	1.2 p.u.
		Integral time	1.65 ms

for the generator current. Consequently, the dc-link voltage and the generator terminal voltage become zero.

IV. Feedback Controls during Voltage Sag

Fig. 8 shows a feedback control block diagram for the FRT operation. As shown in Fig. 1, it is required to control the snubber voltage and the generator current stably during the voltage sag in order to obtain a stable FRT operation and a desired generator torque. Hence, this paper uses two feedback controls for the snubber voltage and the generator current. In particular, the snubber voltage control is defined as an outer loop and the generator current control is set as an inner loop. When the braking IGBT is turned on during the voltage sag, the snubber voltage reference V_{snb}^* is determined according to the active power consumed by the braking resistor R_{brk}, which is equivalent to control the generator torque. On the other hand, inner loop controls the generator dq-axis current according to the voltage sag. PI controllers are employed in to the snubber voltage and the generator current controls. By introducing these feedback controls, the stable FRT operation and the generator torque control are achieved during the voltage sag.

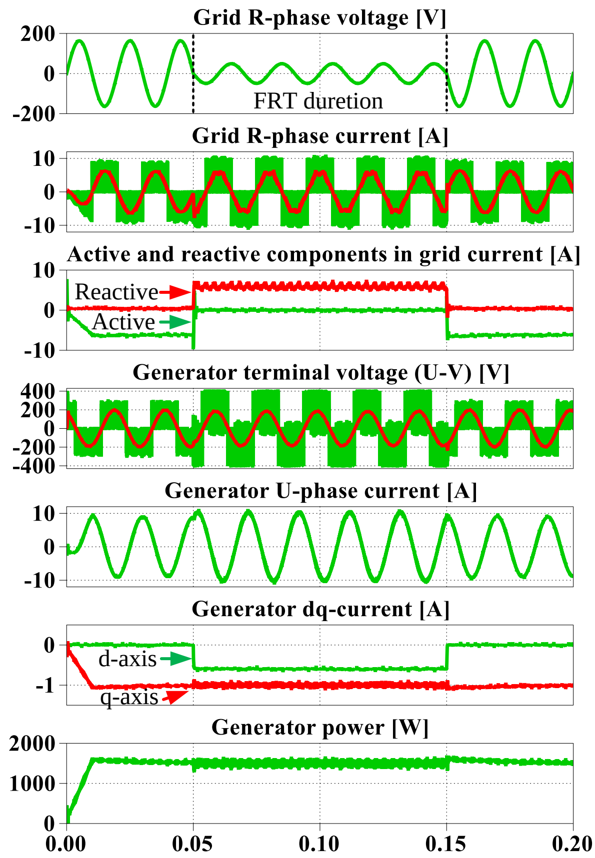

Fig.9. Simulation results of matrix converter during FRT operation.

V. Simulation Results

Fig. 9 shows the simulation results of the matrix converter during the FRT operation under the ideal condition (DC voltage source snubber, ideal commutation and no delay of the voltage dip detection). Table II and III show simulation conditions and control parameters. Note that inductors and a three-phase AC voltage source are used instead of the generator and the q-axis current of the inductors is used to evaluate the generator torque. The theoretical maximum power factor of the generator is cos π/6. In addition, the power factor is slightly decreased in order to obtain the grid reactive current of 1 p.u.. Therefore, the waveforms are not affected by the power factor. The red waveforms of the grid R-phase current and the generator terminal voltage (U-V) in Fig. 9 show the averaged waveforms by using a low pass filter with a cut-off frequency of 1 kHz. In Fig. 9, the voltage sag of 70% occurs and the matrix converter operates with the proposed FRT modulation method during this period. During the FRT operation, the grid active current is reduced to almost zero and the grid reactive current is generated by the zero power factor modulation of the virtual CSR and the DC-link conduction mode of the virtual VSI. The generator terminal voltage (U-V) and the generator current during the voltage sag are sinusoidal waveform. Note that the q-axis current during the voltage sag is kept to 1 p.u. during both the normal state and the FRT operation. This results in the constant generator power of 1500 W, i.e. the constant generator torque. On the other hand, the proposed method increases the d-axis current of the generator in order to obtain the power factor cos $\pi/6$, i.e. the condition to achieve the maximum grid reactive current. Therefore, the expansion of the FRT operation range is achieved by the proposed control.

Fig. 10 shows the relationship between k and the grid reactive current value during the voltage sag. The proportional relationship between the grid reactive current and the ratio k is achieved in both the conventional and proposed FRT method. Therefore, the maximum value is reaches 1.0 p.u.. In the conventional method, the maximum value of the grid reactive current is 0.86 p.u., whereas the maximum value of the grid reactive current in the proposed method increases by 15%.

VI. EXPERIMENTAL RESULTS

Table II and III show experimental conditions and control parameters. This session presents experimental results using a prototype depicted in Fig. 1 to confirm the FRT capability, the grid reactive current and the generator torque controls with the proposed FRT method. Note that inductors and an AC voltage source are used instead of the generator and q-axis current of the inductors is evaluated as the generator torque in experiments. The voltage sag amplitude is set to 70%, i.e. the remaining voltage of 30%. d_{link} is calculated by $d_{link} = k(1- d_X - d_Y)$ in order to obtain the maximum grid reactive current.

Fig. 11 shows the operation waveform of the matrix converter during the three-phase voltage sag. In Fig. 11, the voltage sag of 70% occurs and the matrix converter operates with the proposed FRT method during this period. The grid current and the generator current during the voltage sag are confirmed to be sinusoidal waveform. In addition, the grid power factor is zero during the voltage sag. The grid reactive current is controlled by the zero power factor modulation of the virtual CSR and the dc-link conduction mode of the virtual VSI.

Fig. 12 shows the responses of the snubber voltage and the generator q-axis current. The snubber voltage reference is set to 400 V in order to obtain the same generator torque as before the voltage sag by using the braking resistor. As shown in Fig. 12, the snubber voltage and the generator q-axis current follow their references. As a result, a stable FRT operation is confirmed by the proposed control.

Fig. 13 shows the dq-axis current responses of the generator. The q-axis current reference during the voltage sag are kept to 1 p.u. in both the normal mode and the FRT operation in order to maintain the constant torque of the generator. As mentioned above, the active power generated from the generator during the FRT operation is transferred to the braking circuit by setting the snubber voltage reference to 400 V. Consequently, it is confirmed that the proposed FRT method obtains the same generator torque as before the voltage sag. Note that the ripple component in the dq-axis currents is caused by a zero-phase voltage fluctuation due to a two-phase modulation. On the other hand, the proposed method increases the generator d-axis current of 0.577 p.u. in order to obtain the power factor cos $\pi/6$,

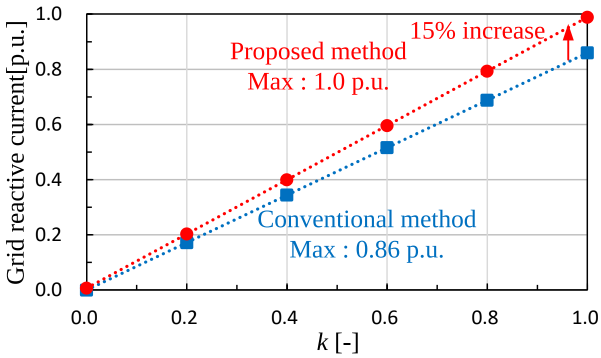

Fig.10. Grid reactive current characteristic with respect to k.

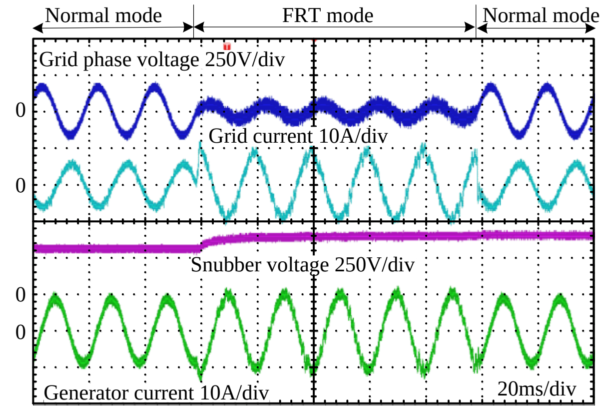

Fig.11. Operation waveform of matrix converter during three-phase voltage sag.

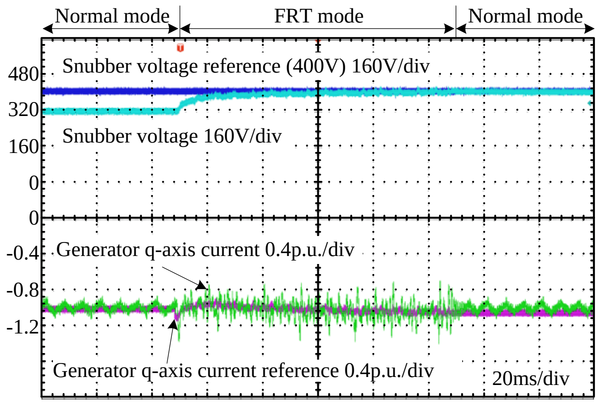

Fig.12. Responses of snubber voltage and generator q-axis current.

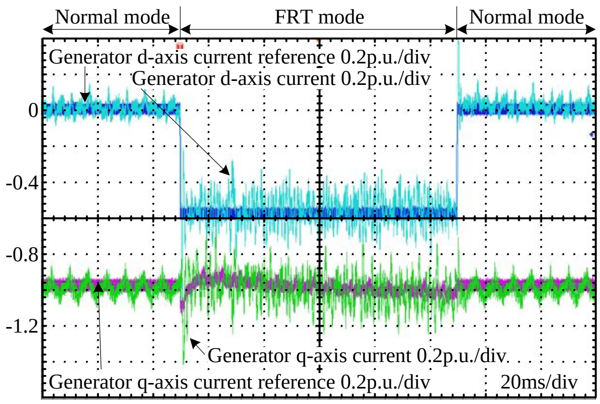

Fig.13. Generator dq-current response.

i.e. the condition to achieve the maximum grid reactive current. The effectiveness of the proposed control method in the experiments is confirmed as same as the simulation. In particular, the proposed method expands the FRT operation range for the grid-tied matrix converter.

Fig. 14 shows the relationship between the voltage sag and the reactive current requirement. The above applies outside a 10% dead band around grid voltage. According to the grid requirements, the reactive current needs to be injected by 0.02 p.u. in response to each 1% of the grid voltage reduction. The range of the conventional FRT method is 43% or less, whereas, the range of the proposed method is 100%. As a result, the range of FRT is expanded by 57pt.

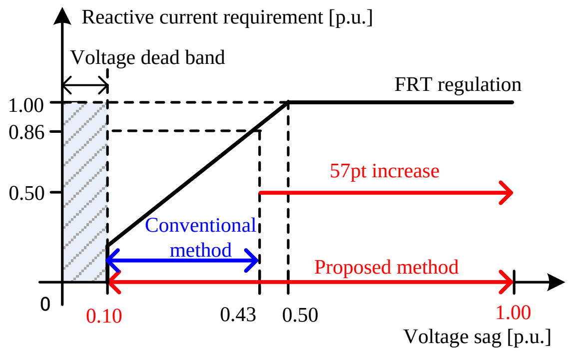

Fig.14. Grid reactive current characteristic with respect to *k*.

VII. Conclusion

This paper proposed the FRT method for the grid-tied matrix converter in order to expand the FRT range. The proposed method maintained the q-axis current to keep the generator torque constant and injected the d-axis current in order to adjust the generator power factor. This increased the maximum grid reactive current, which expanded the FRT range. From the simulation and experimental results, the proposed method realized the stable FRT operation during the voltage sag of 70%. Furthermore, the maximum value of the grid reactive current was increased by 15% as compared to that of the conventional method. Consequently, the range of the FRT operation was expanded by 57pt from 43 % or less to 100%.

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